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1977 MEASUREMENTS OF FLOW FLUCTUATIONS IN THE VKF TUNNELS A AND--ETC(U)
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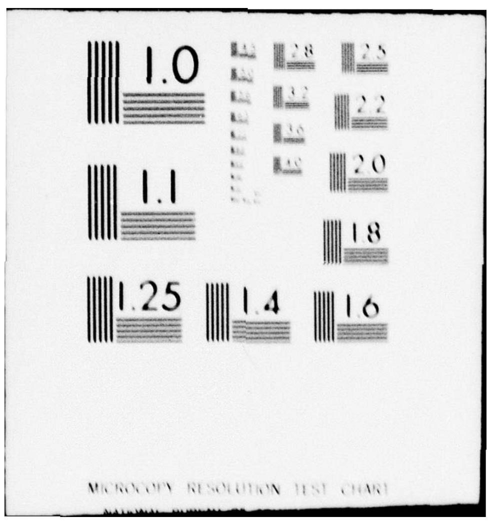
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1977 MEASUREMENTS OF FLOW FLUCTUATIONS IN THE VKF TUNNELS A AND D

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A Sverdrup Corporation Company
von Kármán Gas Dynamics Facility
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The measurement of the fluctuations of flow parameters in the test section of various wind tunnels of the von Kármán Gas Dynamics Facility has been undertaken.. The present report outlines procedures and techniques used in the initial studies of the supersonic Tunnels A and D, during 1977.

Hot-wire anemometry techniques were used to measure fluctuations in the free-stream and boundary-layer flow fields. Dynamic-pressure transducers were used over

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for the measurements at the tunnel walls and at the surface of a representative (flat plate) model mounted in the test section. Sample qualitative results are presented.

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SUMMARY

The measurement of the fluctuations of flow parameters in the test section of various wind tunnels of the von Karman Gas Dynamics Facility has been undertaken. The present report outlines procedures and techniques used in the initial studies of the supersonic Tunnels A and D, during 1977.

Hot-wire anemometry techniques were used to measure fluctuations in the free-stream and boundary layer flow fields. Dynamic-pressure transducers were used for the measurements at the tunnel walls and at the surface of a representative (flat plate) model mounted in the test section. Sample qualitative results are presented.

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NOMENCLATURE FOR TEXT

M	Mach number
p	Pressure, psia
p_o'	Free-stream pitot pressure, psia
q	Dynamic pressure, psia
Re_∞	Reynolds number, $\rho_\infty U_\infty/\mu_\infty$, ft^{-1}
T	Temperature, °R
U	Velocity, ft/sec
v	Anemometer ac response voltage, rms volts
μ_∞	Dynamic viscosity, based on T_∞, lb_f-sec/ft^2
ρ	Density, lb_m/ft^3

Subscripts

ℓ	Local condition in nozzle flow
o	Tunnel stilling chamber condition
p	Pitot pressure probe
w	Wall condition
∞	Free-stream condition

1.0 INTRODUCTION

The work reported herein was conducted by the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), under Program Element 65807S, Control Number 9R02-13-8, at the request of Directorate of Test Engineering, Research Division (DOTR), AEDC. The DOTR project monitor was A. F. Money and the operating contractor project monitor was W. T. Strike. The results were obtained by ARO, Inc., AEDC Division (a Sverdrup Corporation Company), operating contractor for the AEDC, AFSC, Arnold Air Force Station, Tennessee. The test was conducted in the von Karman Gas Dynamics Facility (VKF), during the period of July 15 and 19 and August 18-23, 1977, under ARO Project No. V41A-P2A.

The objective of the testing was to acquire detailed measurements of flow fluctuation parameters associated with supersonic flow in two tunnels of the von Karman Gas Dynamics Facility, Tunnels A and D.

Hot-wire anemometry techniques were applied to determine the level of fluctuations in the flow and dynamic-pressure sensors were used to measure pressure fluctuations at the surface of a flat plate mounted in the tunnel test section. Pressure fluctuations at the wall in the stilling chamber, the nozzle, and the test section were measured. In the Tunnel D study, measurements were also made in the nozzle boundary layer flow field at a station where the tunnel sidewall boundary layer could be maintained with a laminar profile. At this station hot-wire anemometer and pitot pressure profiles were obtained with and without roughness elements attached to the wall. This report describes the flat plate model, survey mechanisms, instrumentation, and test procedures used.

A copy of the final data from this test is on file at AEDC. Requests for copies should be addressed to AEDC/DOTR, Arnold AFS, TN 37389.

2.0 APPARATUS

2.1 WIND TUNNELS

Tunnel A (Fig. 1) is a continuous, closed-circuit, variable density wind tunnel with an automatically driven flexible-plate-type nozzle and a 40- by 40-in. test section. The tunnel can be operated at Mach numbers from 1.5 to 6.0 at maximum stagnation pressures from 29 to 200 psia, respectively, and stagnation temperatures up to 750°R depending upon Mach number and pressure level. Minimum operating pressures range from about one-tenth to one-twentieth of the maximum at each Mach number. The tunnel is equipped with a model injection system which allows removal of the model from the test section while the tunnel remains in operation.

Tunnel D (Fig. 2) is an intermittent, variable density wind tunnel with a manually adjusted, flexible plate-type nozzle and a 12- by 12-in. test section. The tunnel can be operated at Mach numbers from 1.5 to 5.0 at stagnation pressures from about 4 to 60 psia and at stagnation temperatures up to about 80°F.

2.2 MODEL

The flat-plate model used for the testing in both tunnels, A and D, was designed and fabricated by the VKF (Fig. 3). The model has a length of 10 in. and a span of 8 in. and is instrumented with two surface pressure orifices (0.047 in. diam). The leading edge radius is 0.0005 in.

The model was designed to accommodate various dynamic pressure sensors mounted in interchangeable inserts centered in the flat-plate planform. Space was provided within the model to house the connectors and signal pre-amplifiers associated with the sensors. Adapters were fabricated for mounting three Bruel and Kjaer (B & K) condenser-type microphones or two PCB Piezotronics piezoelectric transducers. In each case, sensors of different diaphragm areas were used and arranged side-by-side across the plate with each area centered at 5.0 in. from the plate leading edge. The sensor diaphragms, the adapters, and the inserts were fitted flush with the plate surface.

2.3 INSTRUMENTATION AND PRECISION

2.3.1 Tunnel A Measurements

Tunnel A stilling chamber pressure is measured with a 15-, 60-, 150-, or a 300-psid transducer referenced to a near vacuum. Based on periodic comparisons with secondary standards, the accuracy (a bandwidth which includes 95 percent of the residuals) of these measurements is estimated to be within ±0.2 percent of reading or ±0.015 psia, whichever is greater. Stilling chamber temperature is measured with a copper-constantan thermocouple with an accuracy of ±3°F based on repeat calibrations.

The Tunnel A pressure system uses 15-psid transducers referenced to a vacuum or a variable reference pressure, and having full-scale calibrated ranges of 1, 5, and 15 psia. Based on periodic comparisons with secondary standards, the accuracy is estimated to be ±0.2 percent of reading or ±0.003 psia, whichever is greater.

2.3.2 Tunnel D Measurements

The tunnel stilling chamber pressure measurements were made using a 20- or 60-psid transducer referenced to a near-vacuum. the accuracy of the measurements is estimated to be ±0.2 percent of the reading or ±0.015 psi, whichever is greater. Tunnel total temperature was measured using a copper-constantan thermocouple with an electronic 32 deg F reference. Accuracy of this measurement is within ±2 deg F.

The model surface, tunnel wall, and pitot probe pressures were measured using 15 psid transducers. The accuracy of the transducers and associated data system is estimated to be: ±0.3 percent of reading or ±0.004 psi, whichever is greater, for pressures less than 1.5 psi; ±0.2 percent of reading or ±0.008 psi, whichever is greater, for pressures in the range 1.5 psi to 8 psi; and ±0.08 percent of reading for pressures in the range 8 psi to full scale. The near-vacuum reference pressure for the transducers was measured using a Hastings absolute pressure transducer.

2.3.3 Anemometer Instrumentation

The constant-current hot-wire anemometer instrumentation with auxiliary electronic equipment was furnished out of inventory by the VKF. The anemometer current control (Philco-Ford Model ADP-13) which supplies the heating current to the sensor is capable of maintaining the current at any one of 15 preset levels, individually selected using pushbutton switches. The anemometer amplifier (Philco-Ford Model ADP-12), which amplifies the wire-response signal, contains the circuits required to electronically compensate the signal for thermal lag caused by the finite heat capacity of the wire. The sensor heating current and mean voltage were fed to autoranging digital voltmeters for a visual display of these parameters and to the VKF Bell and Howell Model VR 3700 B magnetic tape machine for recording. The sensor response a-c voltage was fed to an oscilloscope for visual display of the raw signal and to a wave analyzer (Hewlett-Packard Model 8553B/8552B) for visual display of the spectra of the fluctuating signal and was recorded on magnetic tape for subsequent detailed analysis.

2.3.4 Dynamic Pressure Sensors

The dynamic pressure measurements at the surface of the flat plate were made using three B & K condenser-type microphones of 0.5-, 0.25-, and 0.125-in. diameter. A measurement of free-stream pitot-pressure fluctuations was made using a PCB Piezotronics miniature piezoelectric transducer. Wall pressure fluctuation measurements were made with Kulite piezoresistive dynamic pressure transducers mounted flush with the stilling chamber wall, the nozzle sidewall, and the test section wall.

2.4 SUPPORT SYSTEMS AND SURVEY MECHANISMS

For Tunnel A testing the flat-plate model and model boundary layer survey probe rake were mounted using the VKF three-degrees-of-freedom dual-sting support system. The rake could be remotely driven within an envelope in the vertical plane defined by a longitudinal travel of 18 in. and a vertical travel of 14 in. The model and rake assembly could be pitched remotely (as a unit) to angles of attack within the range of ±15 deg. For the present, testing measurements were made only for zero angle of attack, and use of the survey mechanism was generally restricted to positioning the probes for measurements outside of the model boundary layer. The probes were positioned in the model wake for protection when not in use.

For Tunnel D testing, the flat-plate model was mounted on the tunnel horizontal sector. Surveys of the model boundary layer were not included, but measurements were made in the tunnel wall boundary layer.

The Tunnel D sidewall boundary layer survey mechanism (Fig. 4), which was manually driven, was designed to traverse a flow field of four-inch depth, using a linear potentiometer to indicate the distance traveled. A hot-wire anemometer probe and a pitot pressure probe were mounted side by side and the wire and the orifice were aligned to survey at the same tunnel axial station and directly above a dynamic pressure transducer flush-mounted in the tunnel wall (Fig. 4).

3.0 TEST DESCRIPTION

3.1 TEST CONDITIONS

A summary of the principal nominal test conditions in each tunnel is given below.

M_∞	p_o, psia	T_o, °R	q_∞, psia	p_∞, psia	$Re_\infty/ft \times 10^{-6}$
Tunnel A					
4	20	640	1.5	0.13	1.4
↓	30	↓	2.2	0.19	2.1
↓	40	↓	2.9	0.26	2.8
↓	50	↓	3.6	0.32	3.5
↓	60	↓	4.4	0.38	4.2
Tunnel D					
4	4	530	0.30	0.026	0.38
↓	5	↓	0.39	0.033	0.47

A test summary is presented in Tables 1 and 2.

3.2 TEST PROCEDURE

3.2.1 General

In the VKF Tunnel A, the model is mounted on a sting support mechanism in an installation tank directly underneath the tunnel test section. The tank is separated from the tunnel by a pair of fairing doors and a safety door. When closed, the fairing doors, except for a slot for the pitch sector, cover the opening to the tank and the safety door seals the tunnel from the tank area. After the model is prepared for a data run, the personnel access door to the installation tank is closed, the tank is vented to the tunnel flow, the safety and fairing doors are opened, and the model is injected into the airstream. After the data recording is completed, the model is retracted into the tank and the sequence is reversed with the tank being vented to atmosphere to allow access to the model in preparation for the next run.

3.2.2 Tunnel A Testing

Pressure fluctuations at the surface of the flat plate model were measured in the Tunnel A test section using condenser-type microphones (Table 1). Supplementary measurements were made of wall pressure fluctuations in the stilling chamber, nozzle, and test section. Pitot pressure fluctuations in the tunnel test section were also measured using a miniature piezoelectric transducer. This portion of the testing was accomplished without significant difficulty. These data are presented in tabular form in this report.

Hot-wire anemometer measurements were made in the free-stream, in the shock layer above the model, and at the outer-edge of the boundary layer on the model at the axial station of the dynamic pressure sensors (Table 1). It was anticipated that the Tunnel A flow environment would be hostile for the hot-wire sensors; and 16 probes were used during the entry, only four of which yielded useful data. Probe failures were attributed generally to the following causes: improper support of the probe during periods of high loads which led to probe body breakage, inadequate bonding of the hot-wire sensor to its supports which resulted in wire failure under aerodynamic loading, and condensation of water droplets on the probes, especially at the lower Tunnel A supply pressures, which caused wire breakage under the mechanical loads. Hot-wire anemometer data acquisition procedures are discussed below (Section 3.2.4).

3.2.3 Tunnel D Testing

Pressure fluctuations at the surface of the flat plate model were measured using condenser-type microphones and piezoelectric transducers (Table 2). Supplementary measurements of wall pressure fluctuations in the stilling chamber, nozzle, and test sections of the tunnel were also made. In addition free-stream (test section) fluctuations of pitot pressure were measured using a piezoelectric transducer.

The nozzle sidewall boundary layer was surveyed at a station 24 in. downstream of the Mach 4 contour throat (that is 31 in. upstream of the center of the tunnel test section). Pitot pressure and qualitative hot-wire anemometer profiles were obtained at supply pressures of p_o = 4 and 5 psia with smooth nozzle walls. Profiles were also obtained with p_o = 5 psia for cases with the boundary layer disturbed by addition of spherical trip elements to the wall upstream of the survey station and alternately by application of trip elements to the opposite sidewall. The spherical trips were arranged in three vertical rows of five-to-seven elements each and the array was centered approximately 17 in. upstream of the boundary layer survey station. Spheres of 0.093 in. diam were used on the adjacent wall and 0.093- and 0.13-in. diam elements were used on the wall opposite to that of the surveys. Only one trip size on a single wall was used in any case (Table 2).

During the surveys wall pressure fluctuations were measured at the survey station using a piezoelectric transducer. In each profile certain stations (heights above the surface) were selected for quantitative hot-wire anemometer measurements.

3.2.4 Hot-Wire Anemometer Quantitative Data Acquisition

Prior to hot-wire measurements the range of acceptable wire heating currents (wire sensitivities) was defined and the necessary adjustments were made in the instrumentation. The thermal-lag time constant for the wire was determined in the free-stream flow using the square wave technique. This time constant was used for all measurements with the wire. The time-constant variation with wire heating current and Reynolds number across the wall boundary layer in the Tunnel D test will be accounted for in the subsequent data analysis.

Flow fluctuation measurements were made at various selected positions along each of the several boundary layer profiles in Tunnel D. At each position the analog response signals were recorded on magnetic tape for 15 wire sensitivities, including one for which the heating current was set at a low level to determine the electronic noise of the system. Each recording was of five-second duration and included, in addition, the analog response of the dynamic pressure sensor at the wall. Similar procedures were followed for free-stream measurements in both tunnels.

The magnetic tape recordings of the hot-wire anemometer response were validated on-line, and the plotted results were used to asses the quality of the signal at the various wire sensitivities. The recordings were subsequently replayed to obtain the average rms value of the hot-wire voltage fluctuations for broadband signal analysis and the power density spectra of the signals for examination of response content.

3.3 DATA UNCERTAINTY

An evaluation of the influence of random measurement errors is presented in this section to provide a partial measure of the uncertainty of the final test results presented in this report. Although evaluation of the systematic measurement error (bias) is not included, it should be noted that the instrumentation accuracy values (given in Section 2.3) used in this evaluation represent a total uncertainty combination of both systematic and two-sigma random error contributions.

3.3.1 Test Conditions

The accuracy of the basic tunnel parameters p_o and T_o (see Section 2.3) and the two-sigma deviation in Mach number determined from test section flow calibrations were used to estimate uncertainties in the other free-stream properties, using the Taylor series method of error propagation.

	Uncertainty (±), percent					
M_∞	M_∞	p_o	T_o	p_∞	q_∞	Re_∞/ft
Tunnel A						
4	0.5	0.2	0.5	2.4	1.5	1.2
Tunnel D						
4	0.2	0.3	0.4	0.7	0.5	0.7

3.3.2 Test Data

The local free-stream Mach number $M_{\infty,\ell}$ in the nozzle flow in Tunnel D was determined from measurements of pitot pressure p_p and tunnel stagnation pressure p_o. The local wall pressure p_w for boundary layer calculations was defined as the free-stream static pressure associated with $M_{\infty,\ell}$ and p_o. Accuracies (95-percent confidence limits) in the pitot and tunnel stagnation pressure measurements were estimated from repeat calibrations of the instruments. An estimate of the uncertainty which is to be associated with each of the calculated parameters in the Tunnel D nozzle flow has been made, based on an analysis of the propagation of errors for the equations used:

	Uncertainty, percent (±)			
M_p	p_p	$M_{\infty,\ell}$	p_w	M_p
3.8	0.50	0.18	1.1	0.60
2.0	1.9	0.18	1.1	1.2

It should be pointed out that surveys in the nozzle boundary layer were made at a station upstream of the completion of nozzle flow expansion.

Estimates of uncertainties in the flow fluctuations have not been made for the qualitative presentations in this report.

4.0 RESULTS

4.1 TUNNEL A TEST ENTRY

Three condenser-type microphones were used in the flat plate model for measurements in Tunnel A. Signals were recorded for the 0.5-in. and 0.25-in. diam microphones with and without the 0.125-in. microphone connected. An alternate sequence of operation was also used in which the 0.125-in. microphone was used alone and in combination (1) with the 0.25-in. microphone and (2) with both 0.25-in. and 0.5-in. microphones (Table 1). The purpose of employing the various combinations was to determine the electrical interference among the microphones when operated in combination. The sensitivity of the B & K condenser-type microphone is dependent upon the stiffness of the diaphragm, which is a function of the pressure of the air in the vented chamber behind the diaphragm. The microphone sensitivities for the sub-atmospheric environment of the present measurements have yet to be determined. For each set of model measurements the stilling chamber wall, nozzle sidewall, and test section wall pressure fluctuations were also obtained, and the fluctuations of free-stream pitot pressure were monitored. The limited results obtained from hot-wire anemometer measurements in the free-stream and in the shock layer above the flat-plate model are not presented in this report.

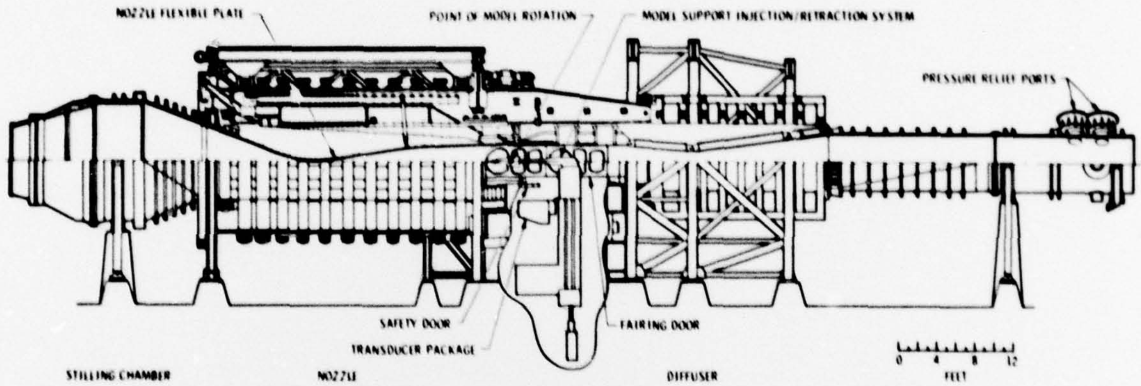
4.2 TUNNEL D TEST ENTRY

Three condenser-type microphones were used for the flat-plate measurements in Tunnel D, and data were recorded for each microphone with the other two disconnected to insure freedom from electrical interference among the sensors and subsequently were recorded with all microphones connected to help assess the interference problems. The levels of the derived pressure fluctuation for the largest microphone (0.5 in. diam) were not consistent with those for the other microphones. The data for all microphones have been reduced using sensitivities applicable to an atmospheric pressure environment. Measurements were also made using piezoelectric transducers but the results are considered to be subject to question because of possible effects of direct contact between the body of each transducer and the nylon adapter which was used to mount the transducers in the model.

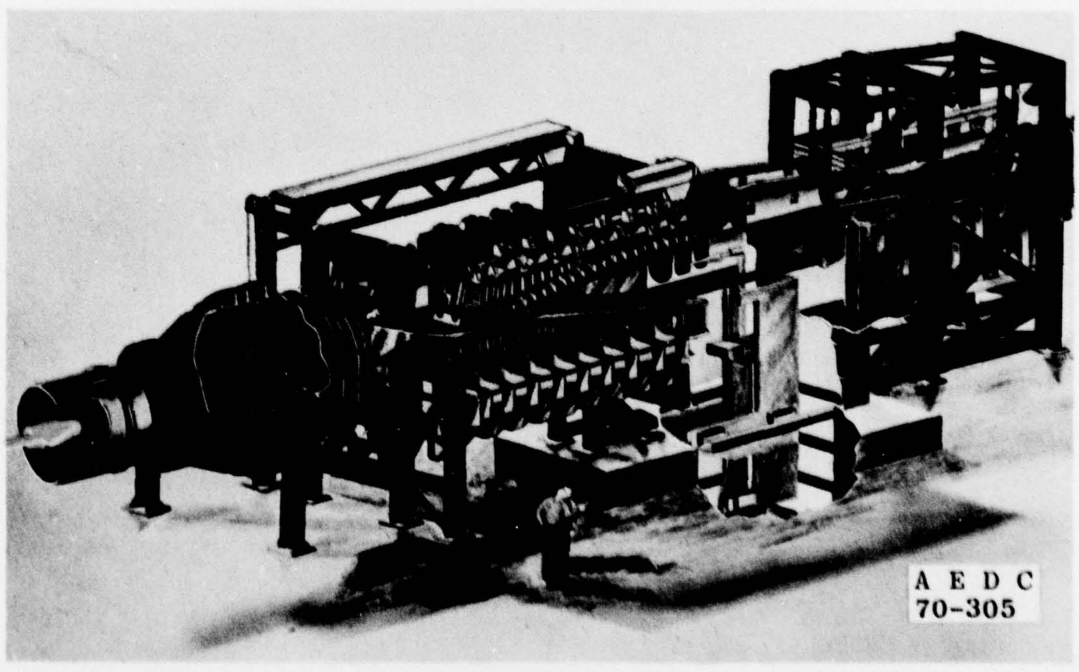
Selected hot-wire anemometer results are shown in Figs. 5a, b, c as an indication of the nature of the findings. In Fig. 5a, data are shown for the nozzle sidewall boundary layer with the minimum tunnel supply pressure of p_o = 4 psia and with nominally-clean nozzle walls. The analog plotter trace of the hot-wire rms response signal (constant heating current) as the probe traversed the boundary layer is shown in the upper-left section of the figure. The bandwidth for the rms response was set for 100 kHz. Pitot pressures normalized by calculated test-section free-stream pitot pressure are shown in the upper-right section. The relative energy content of the hot-wire response (ac) signals at different stations along the profile is indicated in the power density spectra presented in the lower half of the figure. The numerical labels refer to the stations indicated on the hot-wire profile. The electronic noise of the anemometer instrumentation is seen to be relatively large, especially when it is related to the wire response outside of the boundary layer (station "1"). The noise spectrum shown is detected at the output of the anemometer amplifier which includes circuits to compensate for sensor thermal lag (see Section 2.3.3). The signal-to-noise ratio can be improved by using a smaller-diameter wire for the sensor (less compensation required), when aerodynamic loads permit. When the signal-handling capabilities are available, it is theoretically possible to acquire data with an under-compensated hot wire (less electronic noise) and subsequently apply mathematical techniques to complete the compensation. The procedures required are very time-consuming in the absence of computer-controlled signal analysis and data handling. These capabilities are not currently available in the von Karman Facility. It should be pointed out that the present signals, beyond a frequency of 140 kHz, show the influence of an impedance mismatch for the cables used to transmit the signals to the magnetic tape recorder. For Fig. 5a, it is estimated that the signal level has been reduced by 9 db at 200 kHz, as a result of this mismatch.

In Figure 5b data for the nozzle sidewall boundary layer with p_o = 5 psia are shown for the smooth-wall case, while in Fig. 5c data are shown for the corresponding case in which 0.093 in. diam spherical trips were attached to the wall upstream of the survey station. Examination of the velocity profiles (not shown) for the test conditions of Figs. 5a, b, c indicate that the boundary layer flow without tripping was laminar for p_o = 4 psia and transitional for p_o = 5 psia.

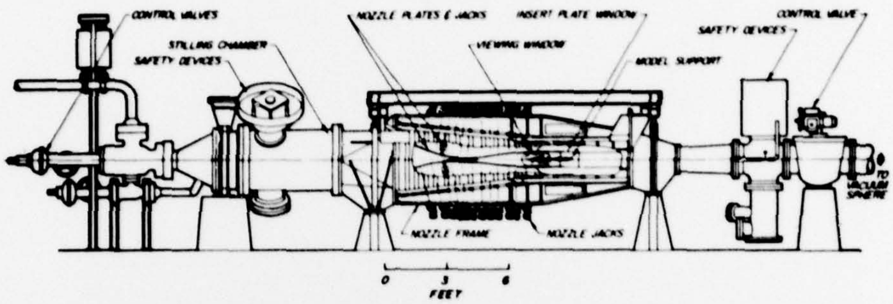
ILLUSTRATIONS



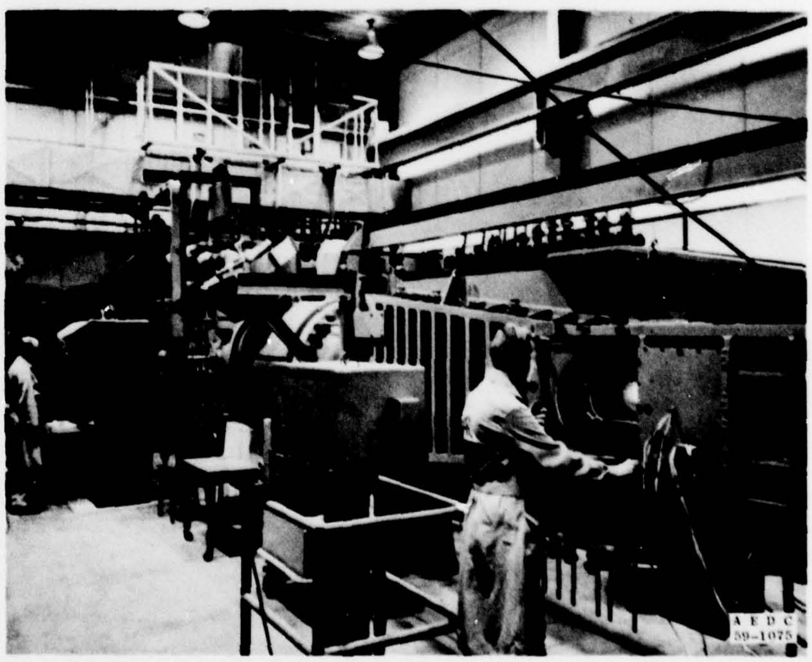
a. Tunnel assembly



b. Tunnel test section
Fig. 1 Tunnel A



a. Tunnel assembly



b. Nozzle and test section

Fig. 2 Tunnel D

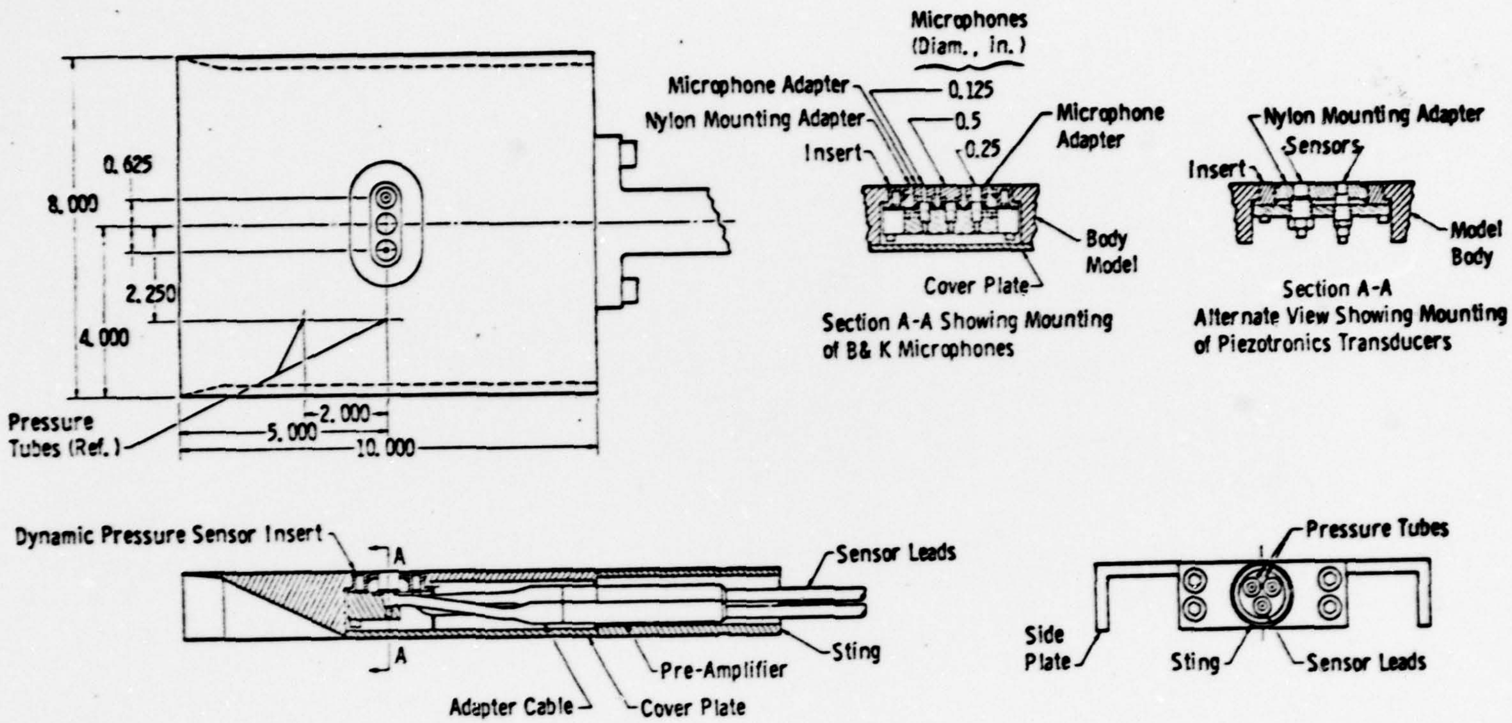


Figure 3. Flat-Plate Model

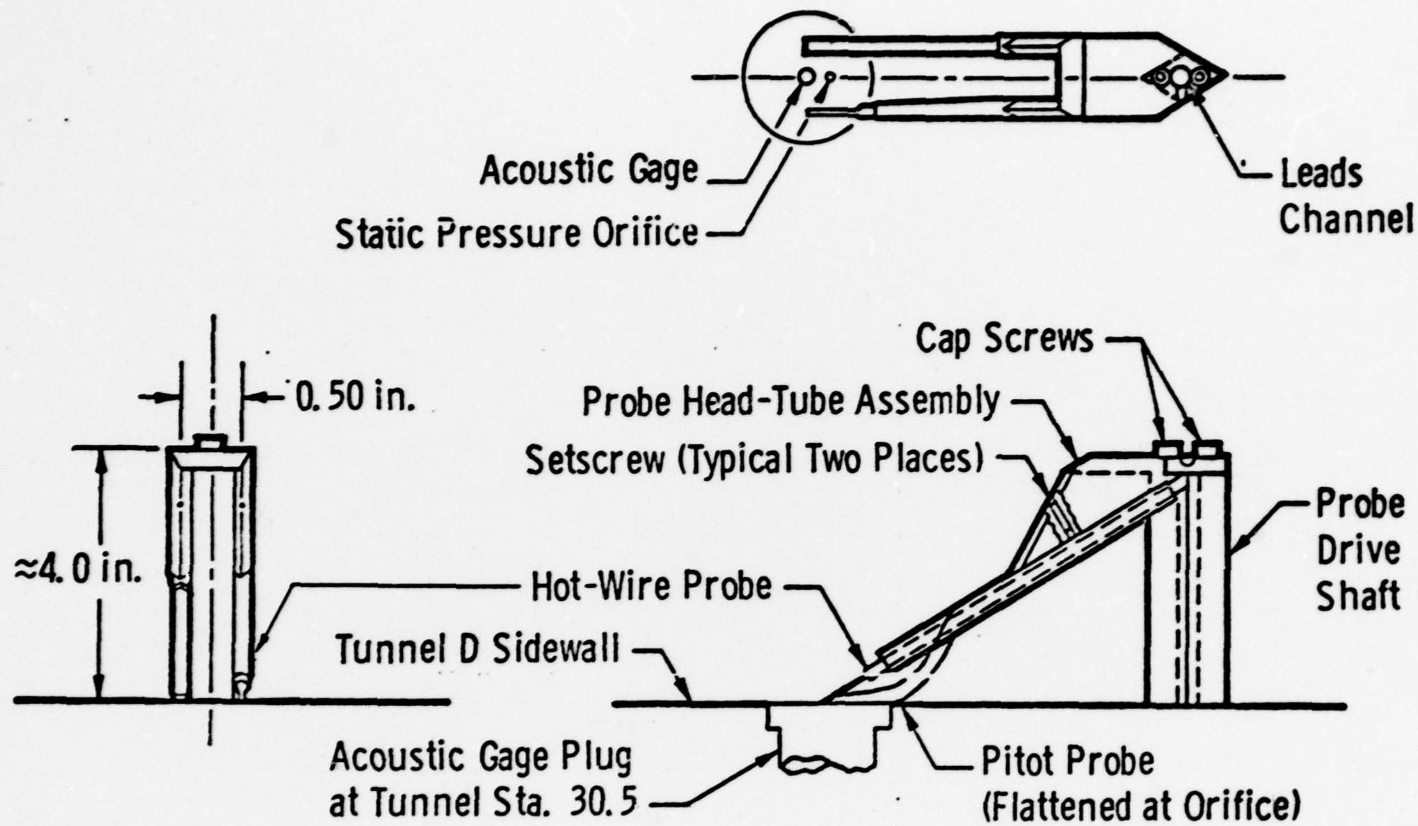
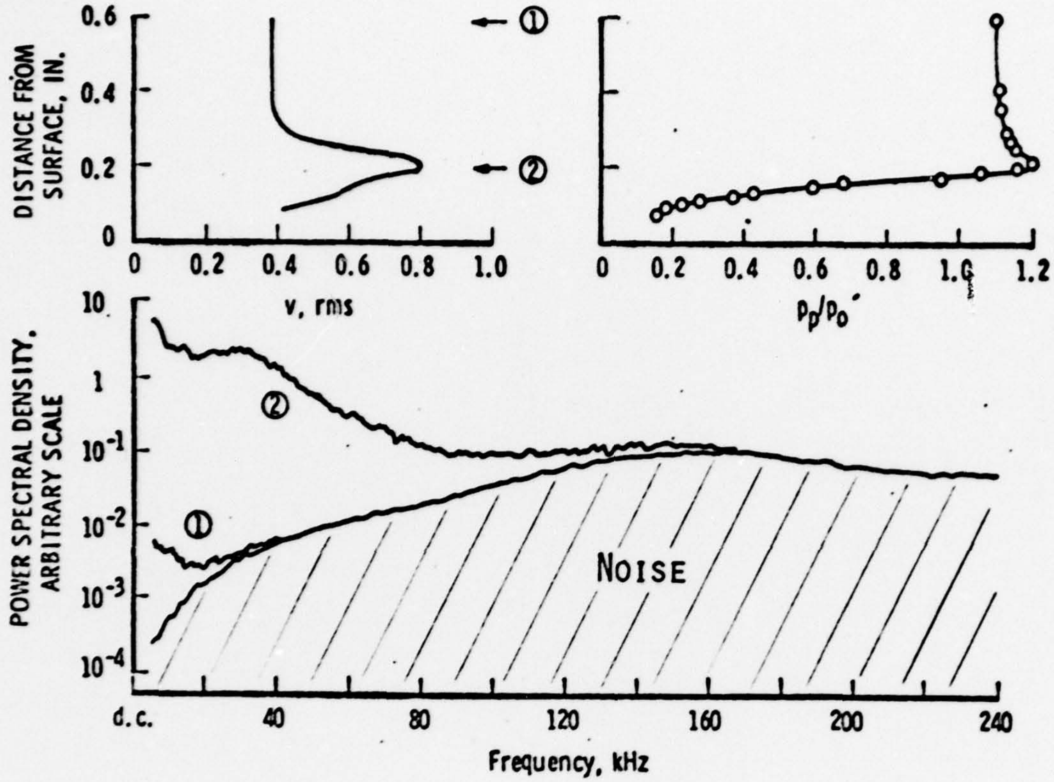
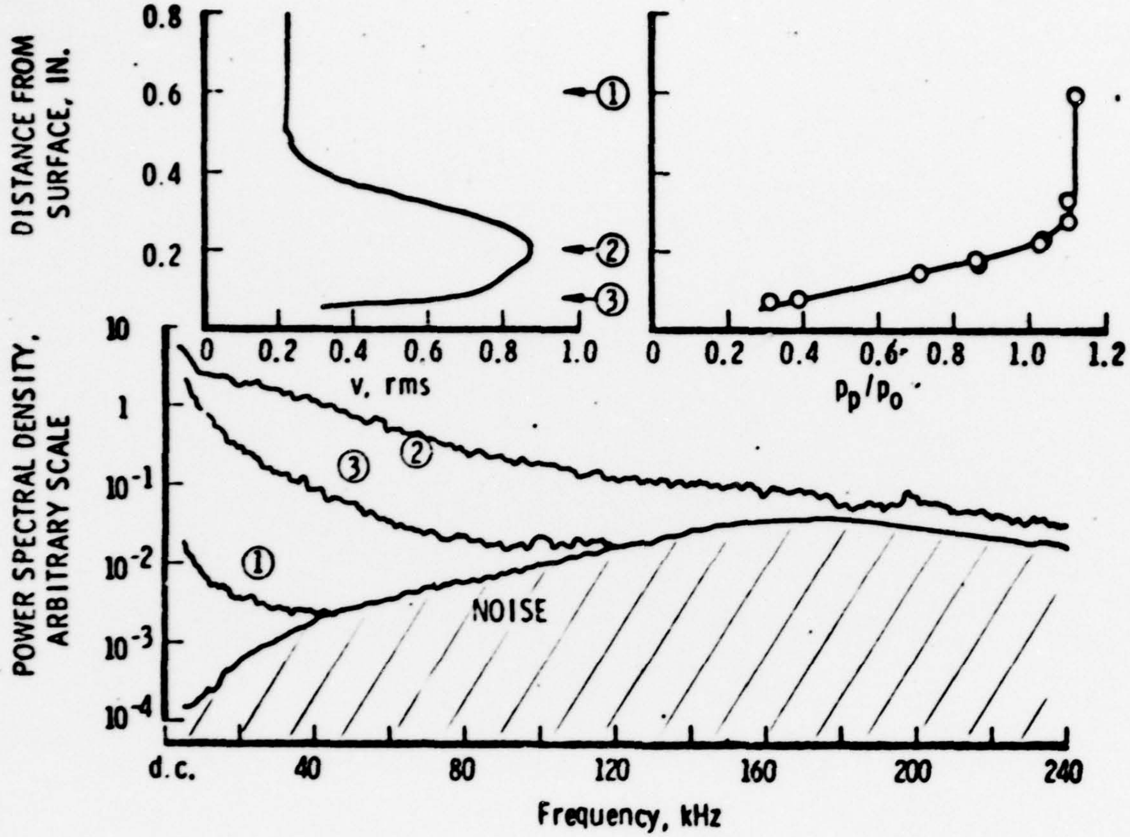


Figure 4. Survey Probe Assembly for Tunnel D



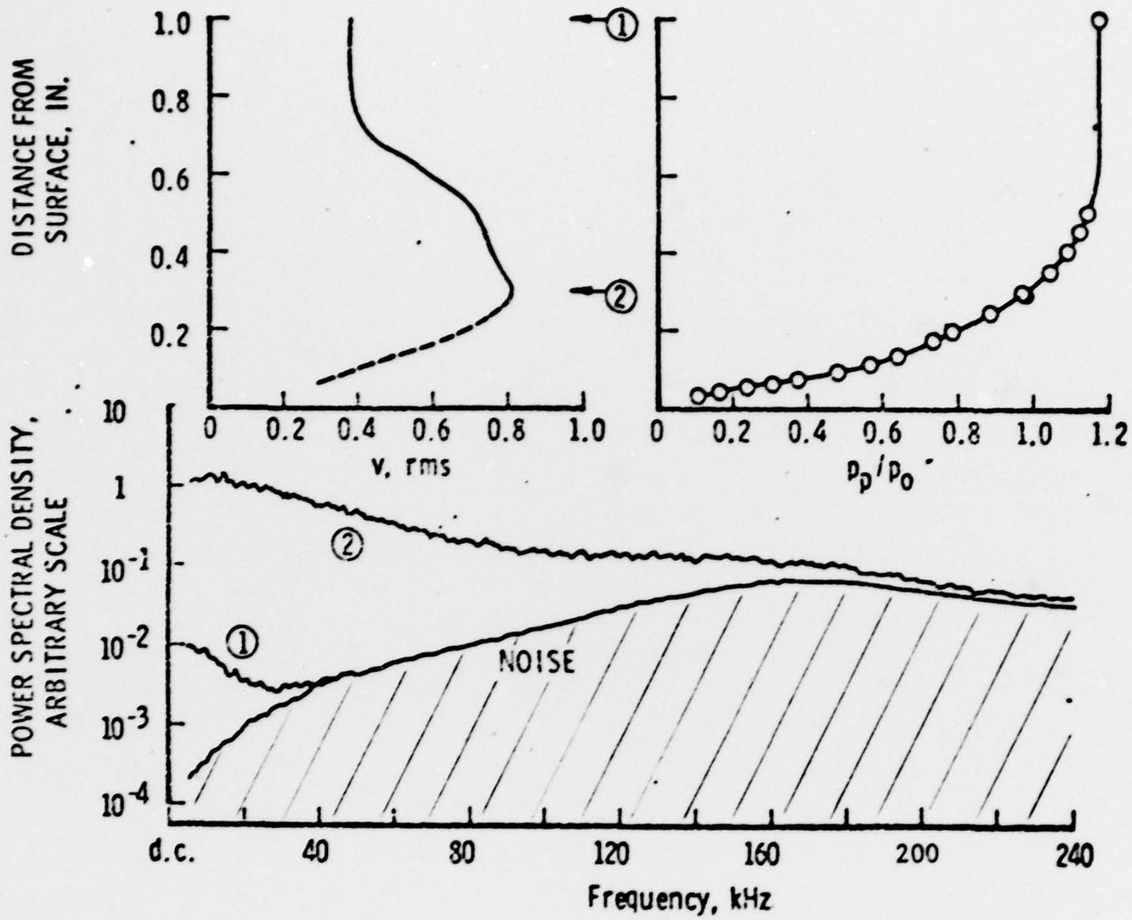
a. Smooth Wall, p_o = 4 psia

Figure 5. Typical Results of Nozzle Wall Boundary Layer Surveys



b. Smooth Wall, p_o = 5 psia

Figure 5. Continued



c. Wall with 0.093 in. Diam Spherical Trips, p_o = 5 psia

Figure 5. Concluded

Table 1

TUNNEL A TEST SUMMARY

FLAT PLATE PRESSURE FLUCTUATION MEASUREMENTS

Condenser - Type Microphones*			Tunnel Supply Pressure P_o, psia						Angle of Attack (deg)
0.5	0.25	0.125	20	30	40	50	60	73	
x	x	x	x	x	x	x	x	x	0
x	x			x	x	x	x	x	
x		x	x	x	x				
		x	x	x	x				
x	x	x						x	+1
x	x							x	
x	x	x						x	-1
x	x							x	

HOT-WIRE ANEMOMETER MEASUREMENTS

Free-Stream Meas.	Shock Layer Meas.	Boundary Layer Edge Meas.
P_o = 40 psia	P_o = 40 psia	
= 50 psia	= 50 psia	
= 60 psia		P_o = 60 psia

* Note: Microphone body diameters shown in inches.

Table 2

TUNNEL D TEST SUMMARY

FLAT PLATE PRESSURE FLUCTUATION MEASUREMENTS

Condenser - Type Microphones*			Piezoelectric Transducers*		Tunnel Supply Pressure P_o, psia							Roll Angle (deg)
0.5	0.25	0.125	0.218	0.405	6	10	15	20	30	45	60	
x						x	x	x	x	x	x	0
	x					x	x	x	x	x	x	
		x				x	x	x	x	x	x	
x	x	x				x	x	x	x	x	x	
			x	x	x	x	x	x	x	x	x	
			x	x	x	x	x	x	x	x	x	-90
			x	x	x	x	x	x	x	x	x	-45

HOT-WIRE ANEMOMETER MEASUREMENTS

Boundary Layer Trips	Boundary Layer Profiles	Free-Stream Meas.
Smooth walls	For p_o = 4 & 5 psia	For p_o = 4-30 psia
0.13 in., on opposite wall	For p_o = 5 psia	---
0.093 in., on opposite wall	"	---
0.093 in., on adjacent wall	"	For p_o = 5-30 psia

*Note: Microphone and transducer diameters shown in inches.